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FOR MINIMUM-ALTITUDE INTERCEPTION

by

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Engineering Design of Guidance Laws for Minimum-Altitude Interception

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Abstract

This paper briefly discusses two guidance laws, used for minimum altitude (or sea-top) target interception in remote guidance: K-prepositioned point method and e-prepositioned point method. Also it explains some major factors to be considered in their design, and the design methods and procedures are given which are based on them.

Key words: guidance law; missile guidance; prepositioned guidance method

Design of the guidance laws is a major integral part of the design of the guidance control system (hereinafter referred to as the system). The requirements set for these laws, as stated in the design of the system, basically involve some problems concerning the type of trajectory generated, summed up roughly as follows:

(1) One of the central problems in designing guidance laws is the nature of the normal acceleration of the trajectory, which is related directly to the guidance precision: with high and drastically changing modulo values of normal acceleration, the target-miss rate would be increased under the same system conditions. Thus, the normal overload value is generally required to be as low and smooth as possible, i.e. the trajectory

should be as flat as possible. In addition to the direct effect on guidance precision as described above, the trajectory flatness will also bring benefits in many other ways. For instance, the requirements for engine charge capacity can be decreased owing to the high flight speed and short flight time and concurrently, low normal acceleration may result in decreased requirements for the operating system. All these favorable aspects will contribute to reducing the missile weight and can possibly raise the warhead charge capacity to reach the goal of enhanced combat efficiency of the weapon system or lowered cost of the missile proper.

(2) Another critical problem in designing guidance laws is the sensitivity of the type of trajectory to target mobility. How to intercept a mobile target has become a subject significant to the design of weapon systems. The mobility of the target, continuously improved with advances in technology, will affect the guidance precision and naturally, its capacity to adapt to such mobility will be considered as a central aspect in evaluating the design of the guidance laws.

(3) Some of the special requirements stated for the trajectory type are also problems to be solved in designing the guidance laws. For instance, the requirement of minimum-altitude (or sea-top) flight as a condition indispensable for intercepting a minimum-altitude target. In addition, the requirement of trajectory link-up among different guidance periods in compound guidance should also be satisfied in the above design.

It is then maintained that the requirements for designing guidance laws, though apparently involving the trajectory type, eventually fall into two categories: "guidance precision" and "special requirements". Correspondingly, there are two types of design corresponding to the above two problem categories. Designing the guidance laws based on guidance precision will not be discussed here because it has been examined by many other

papers. The following description involves some problems concerning the design that are based on the special requirements --mainly minimum-altitude reception, with the guidance pattern limited to the remote guidance area.

In the remote guidance pattern, the commonly used guidance law is positional guidance, for which the equation is generally expressed as follows:

$$\varphi_m = \varphi_\tau + K_\varphi \Delta R \qquad (1)$$

where ϕm radius vector-directional angle of the missile

$\phi\tau$ radius vector-directional angle of the target

ΔR relative distance between the target and the missile

K_ϕ guidance coefficient--either a constant or a particular form of function

The major concern in designing the guidance laws is how to determine the guidance coefficient K_ϕ. The design of the variation of K_ϕ Obviously, if $K_\phi=0$ is taken, the guidance becomes the commonly used three-point method. Equation (1) shows that if we let

$$\Delta\varphi = K_\varphi \Delta R \qquad (2)$$

then

$$\Delta\varphi = \varphi_m - \varphi_\tau$$

$\Delta\phi$ is usually referred to as position prepositioned angle, while the guidance method of $\Delta\phi \neq 0$ is called the prepositioned point method. It can be seen from equation (2) that when $\Delta R=0$ then the position prepositioned angle $\Delta\phi=0$, signifying an unavoidable collision between missile and target in space is ensured in the kinematic sense, and that $K\phi$ can be determined according to different requirements so as not to affect such a collision. This is the foundation based on which the special requirements can be met by using the guidance law in designing the system.

The special requirements refer to some constraints which, being necessary for a normal guidance process, serve as a prerequisite, without which the required guidance precision could not be reached. Such requirements may be classified as different kinds, including requirements for flight altitude of a missile intended to intercept a minimum altitude (or sea-top) target.

As far as minimum-altitude (or sea-top) target interception is concerned, the high-low angle of the target radius vector (ε_T) and its variation rate ($\dot{\varepsilon}_T$) can be expressed in the following equation:

$$\begin{cases} \varepsilon_T \approx H_T / R_T \\ \dot{\varepsilon}_T \approx -V_T \varepsilon_T / R_T \end{cases} \tag{3}$$

where H_T is the target flight altitude. Since its value is very low (assumed to be a constant for the sake of discussion), far lower than its slant distance, i.e. $H_T \ll R_T$, both the high-low angle of the target and its variation rate will also be fairly low. The position guidance equation (1) is commonly expressed in the following form:

$$\varepsilon_m = \varepsilon_T - (\eta \Delta R / \Delta \dot{R}) \dot{\varepsilon}_T \tag{4}$$

where ε_m is the high-low angle of the missile;
η is the guidance coefficient.

Equation (4) indicates that the high-low angle of the missile will be equally low at that time. Thus, the flight altitude of the missile will be very low during guidance (especially in the initial flight period). As a result, its kinetic parameters will be difficult to measure, normal functioning of its fuse may weaken and the missile itself may

touch ground or crash into the sea. If this situation actually happens, then the normal guidance process can not be fulfilled and the target will be missed. Under this condition, two categories of problems have been put forward: the first one is to increase the altitude of the missile during the initial flight period, while the second one is to increase the altitude of the missile throughout the guidance process except when the missile is approaching the target and has to be adjusted to the altitude of the latter near the point of encounter so as to hit it.

In accordance with the above two categories of problems, the two following methods have been adopted in engineering which have proven effective in practice.

1. K-Prepositioned Point Method

The semi-prepositioned point method is a common guidance method used in positional guidance. Its equation (taking the high-low direction as an example) can be expressed as:

$$\varepsilon_m = \varepsilon_T - \frac{1}{2}\Delta R \dot{\varepsilon}_T / \Delta \dot{R} \tag{5}$$

This guidance method has the advantage of ensuring higher guidance precision, i.e. it can not only increase the missile flight altitude to intercept a minimum altitude target, but also maintains the basic advantage of the semi-prepositioned point method--satisfying the requirement for precision guidance. The equation of this guidance law in the high-low direction has been formulated as follows:

$$\varepsilon_m = \begin{cases} \varepsilon_T - K\Delta R / 2\Delta \dot{R} & \dot{\varepsilon}_T \leqslant K \\ \varepsilon_T - \dot{\varepsilon}_T \Delta R / 2\Delta \dot{R} & \dot{\varepsilon}_T > K \end{cases} \tag{6}$$

where K is the parameter to be designed which can be either a constant or a certain form of function. It can be seen from equation (6), when $\dot{\varepsilon}_T$ is very low (the missile is now at the initial flight period), the prepositioned angle $\Delta\varepsilon_K$, can be increased if a certain appropriate K value is taken,

$$\Delta\varepsilon_K = K\Delta R / 2\Delta\dot{R} \tag{7}$$

This, obviously, will increase the high-low angle of the missile and then increase its flight altitude in the initial period. In the final flight period, however, the high-low angle velocity of the target will be increased so much as to exceed the K value taken, meaning that the semi-prepositioned point method is resumed. Therefore, K value should be chosen in the first place to meet the need of adjusting and restoring this guidance method.

When the K-prepositioned point guidance method is derived by inference from equation (6), the expression of the normal missile acceleration will be simple and striking. Below we give the expression when ΔR equals zero as follows (taking the description of the high-low direction as an example):

$$\begin{cases} a_{m\varepsilon} = F_1(\dot{\varepsilon}_T - K/2) + F_2 R_m \\ F_1 = 2\dot{R}_m - R_m \dot{V}_m / V_m \\ F_2 = \ddot{\varepsilon}_T - K\Delta\ddot{R} / 2\Delta\dot{R} + \frac{1}{4}\dot{\beta}_T^2 \sin\varepsilon_T \cos\varepsilon_T \end{cases} \tag{8}$$

Equation (8) suggests that the character of the trajectory normal acceleration can be changed by introducing the K value, and the effect of target mobility can not be eliminated at the encounter point. Hence, the K value is usually intended to be applied only in the initial flight period and will be replaced by the semi-prepositioned guidance method when the missile is about to encounter the target.

In the K-prepositioned point method, apparently, the major

parameter to be chosen is none other than the K value to be taken. In this case, the main factors that usually should be considered are: the low-far boundary parameter of the space area within the kill-range of the weapon system, the maximum normal g-overload the missile can withstand, the allowable minimum flight altitude and the field of vision of the scanning equipment, etc. The selection of the K value can generally be summed up as follows:

The relationship of minimum-altitude interception is derived as follows:

$$\begin{cases} \sin(\varepsilon_{T\min} + \Delta\varepsilon_K) \approx \varepsilon_{T\min} + \Delta\varepsilon_K \\ \sin\varepsilon_{T\min} \approx \varepsilon_{T\min} \end{cases} \tag{9}$$

Concerning the kill-space area and the minimum allowable flight altitude of the missile, the following equation can be obtained from equation (9):

$$\Delta\varepsilon_K \geqslant |H_{m\min} / R_o - H_{T\min} / R_{T\max}| \tag{10}$$

where $H_{m\min}$ is the allowable minimum flight altitude of the missile;

R_0 is its oblique distance value taken before the missile enters the target-scanning field;

$H_{T\min}$ is the minimum flight altitude of the target;

$R_{T\max}$ is the maximum slant distance of the target while the missile is being launched, which corresponds to the farthest and lowest boundary point within the kill-space area. If the constraint of the field of view of the scanning equipment is taken into account, the prepositioned angle should also satisfy the following expression:

$$\Delta\varepsilon_K < \mu\varphi \tag{11}$$

where ϕ is for the parameters of the field of vision of the canning equipment, including the parameter of the radar beam width, the parameter of the infrared goniometer field of view in the high-low direction, etc;

μ is the coefficient taken.

From equations (12) and (13), the following can be obtained:

$$K \geqslant \left|\frac{2\Delta \dot{R}_o}{\Delta R_o}\left(\frac{H_{m\min}}{R_o} - \frac{H_{T\min}}{R_{T\max}}\right)\right| \tag{12}$$

or

$$K \geqslant |2H_{m\min} \Delta \dot{R}_o / R_o \cdot \Delta R_o| \tag{13}$$

where ΔR_o and $\Delta \dot{R}_o$ can be taken when determining the R_0 value according to the circumstances.

Equations (12) and (13) can be accepted as the first reference condition for determining the K value.

The second restrictive condition for determining K can be derived from equations (7) and (11):

$$K < |(2\Delta \dot{R}_o / \Delta R_o) \cdot \mu\varphi| \tag{14}$$

When possible maximum normal acceleration is under consideration, the third restrictive condition for determining the K value can be given according to equation (8) as follows:

$$|a_{m\varepsilon\max}| \geqslant |a_{m\varepsilon o} - a_{m\varepsilon K}| \tag{15}$$

where $a_{m\varepsilon\max}$ is the component of the possible maximum normal acceleration in the high-low direction;

$a_{m\varepsilon o}$ K is the normal acceleration component generated by the high-low angle velocity of the target $(\dot{\varepsilon}_T)$ and others, in the K-prepositioned point method. For instance, when ΔR equals zero, its expression will be:

$$a_{m\varepsilon o} = F_1 \dot{\varepsilon}_T + (F_2 + K\Delta \ddot{R} / 2\Delta \dot{R}) R_m$$

$a_{m\varepsilon K}$ K is the component of the normal acceleration, based on K, in the high-low direction in the K-prepositioned point method. For example, when ΔR equals zero, its expression will be:

$$a_{m\varepsilon K} = K(F_1 - R_m \Delta\ddot{R} / \Delta\dot{R}) / 2$$

Under the condition when the missile is flying at a minimum value altitude, if $\ddot{\varepsilon}_T$, $\dot{\varepsilon}_T$ and ε_T are too small to be taken and the following approximate value is adopted:

$$a_{m\varepsilon o} \approx 0$$

then equation (15) can be written as:

$$|a_{m\varepsilon K}| \leqslant |a_{m\varepsilon\max}| \qquad (16)$$

Generally, selection of K value is completed in the following steps: first, make a preliminary choice of the value based on equation (12) or (13) or (14); then selecting a number of typical encounter points within the kill-space area, which then are verified by calculation using (15) or (16); and finally, determining the K value through a simulation check calculation and adjustment of the trajectory control at those encounter points selected. Of course, the final K value will not be decided until it is confirmed by an actual flight trial of the missile.

2. e-Prepositioned Point Method

As mentioned above, with regard to intercepting a minimum-altitude target, some special requirements might be proposed, apart from increasing the flight altitude of the missile in its initial flight period, throughout the whole guidance process, such as the requirement that the high-low angle of the radius vector of the missile always be higher than that of the target radius vector throughout the guidance process, until the missile arrives at the encounter point when the two angles can be equal,

so that the scanning equipment can collect information about both the target and the missile high-low angles, and so on. This is because the performance of the scanning equipment is limited, such as the limited ability to discriminate data from the target and data from the missile. This is another category of problems that designing guidance law confronts. To solve these problems, one possible technical approach is to adopt a form of index attenuation of the position prepositioned angle, i.e. the e-prepositional point method as a simplified term. Its guidance equation can be expressed as:

$$\begin{cases} \varepsilon_m = \varepsilon_T + \Delta\varepsilon_E \\ \Delta\varepsilon_E = \begin{cases} h_o(1 - e^{-T_R \Delta R}) / R_m & H_T \leqslant H_o \\ \Delta R \dot{\varepsilon}_T / 2\Delta \dot{R} & H_T > H_o \end{cases} \end{cases} \tag{17}$$

where h_0 is the constant taken;

H_0 is the altitude boundary constant taken and

T_R is the attenuation coefficient.

According to equation (17), the guidance equation in minimum-altitude interception can be written as:

$$\varepsilon_m = \varepsilon_T + h_o(1 - e^{-T_R \Delta R}) / R_m \tag{18}$$

In this form, h_0 and T_r are parameters to be selected, for which there are two major requirements;

(1) The longer the slant distance of the encounter point and the nearer the flight distance of the missile, the higher the position prepositioned angle $\Delta\epsilon_E$ will be and

(2) When the relative distance ΔR approaches zero, the position prepositioned angle $\Delta\epsilon_E$ can maintain zero, so that in a

short while the missile can surely hit the target.

Equation (18) shows that the introduction of the position prepositioned angle is virtually equivalent to increments of the missile flight altitude in the sense of kinematics ΔH. Its value is:

$$\Delta H \approx h_o(1 - e^{-T_R \Delta R}) \tag{19}$$

or

$$\Delta H_{\max} = h_o \tag{20}$$

Based on equation (19) or (20), the first reference condition for determining h_0 can be obtained, i.e.

$$h_o > (H_{m\min} - R_{mo} \sin\varepsilon_{To}) \tag{21}$$

where R_{m0} is the maximum slant distance of the missile in minimum-altitude interception and

ϵ_{T0} is the high-low angle of the target, which corresponds to R_{m0}.

Under the condition of minimum-altitude interception, its value can be taken as:

$$\varepsilon_{To} \approx 0$$

Then equation (21) can be given as

$$h_o > H_{\min} \tag{22}$$

If the constraint of the field of view of the scanning equipment is taken into account, the second constraint condition for determining h_0 can be derived as follows:

$$\Delta\varepsilon_E < \mu\varphi$$

or

$$h_o < \mu\varphi R_m \tag{23}$$

Like the K-prepositioned point method, here the third constraint condition of verification can also be obtained with the component of the possible maximum normal acceleration in the high-low direction, which can be expressed as follows:

$$|a_{m\varepsilon\max}| \geqslant |a_{m\varepsilon o} + a_{m\varepsilon E}| \tag{24}$$

where $a_{m\varepsilon E}$ is the component of the normal acceleration component, generated by the prepositioned angle with the introduction of the index attenuation in the high-low direction. If $a_{m\varepsilon 0}$ is ruled out, equation (24) can be taken as $|a_{m\varepsilon E}| < |a_{m\varepsilon\max}|$。

Selecting parameter T_R mainly depends on two factors given below:

(1) The requirement of raising the altitude attenuation velocity, especially near the encounter point;

(2) Various requirements for raising the altitude (including its attenuation velocity) within the kill-space area, particularly the coordination between the near and far boundaries of the above-space area.

According to the two factors above, T_R can be taken as either a certain constant or a function of the parameter of the kill-space area. For instance, if T_R is taken in direct proportion to the encounter point slant distance, then the distance will be farther, the altitude of the missile in its initial flight period will be increased more and the attenuation velocity will be slower.

The steps in selecting h_0 and T_R appear to be the same as in

selecting K in the K-prepositioned point method as mentioned above.

In short, the foregoing discussion is devoted to the two forms of guidance laws which can be used in minimum-altitude (or sea-top) target interception, together with a brief explanation of the methods and procedures of their engineering design. Of the two forms suggested, the K-prepositioned point method is designed to satisfy the requirement of raising the requirement of raising the missile flight altitude in its initial flight period, while the e-prepositional point method is designed to meet the requirement of increasing the altitude of the missile throughout the flight. Obviously, by designing the guidance laws, the system can adapt to the special requirements set for the minimum-altitude (or sea-top) target interception. Of course, it is possible to adopt other guidance equations, but the restrictive conditions that should be considered in their design will probably be approximately those discussed in this paper.

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